Z boson production in Pb plus Pb collisions at root S-NN=5.02 TeV measured by the ATLAS experiment

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Isotopic effect in half-wavelength-crystal channeling of relativistic ions

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The computer simulations of the angular distributions of low-Z relativistic isotopes channeled in a half-wavelength-crystal (HWC) revealed that at equal beam energy, crystal thickness and its alignment, the HWC channeling is sensitive to a mass number A of the low-Z isotope. That means, besides well-known applications of relativistic channeling for beam deflection and splitting, probably the new one is possible – light isotopes mass filter.

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1. Introduction

A half-wavelength-crystal (HWC) is a thin crystal where a channeling particle experiences only one collision with the crystallographic plane (so-called “mirroring”) during its penetration through the HWC, see for more details in Fig. 1 and Fig. 2 (a-c). The experiment [1] demonstrated the effect of mirroring of 2 MeV protons by silicon HWC. The experiment [2] at CERN-SPS demonstrated the mirroring effect for 400 GeV protons. Recently, the experiments [3–5] at the SAGA-LS Facility revealed an existence of HWC channeling for negative charged particles -255-MeV electrons in a thin Si HWC. The HWC channeling effect, as explained in computer simulations, is a sequence of the specific trajectories of particles, governed by the one-dimensional periodic potential of crystallographic planes. This effect was first predicted by computer simulations in Ref. [6], in connection with studies of crystal-assisted extraction of 1-TeV beam halo protons from the Tevatron. The perspective atomic physics experiments (including crystal targets) with relativistic heavy ion (RHI) beams are the part of the Super-FRS Experiment Collaboration Program [7,8]. The specific case of this compared to [1–5] is a possibility to vary both the charge and mass of the projectile. The first successful experiment on RHI channeling at GSI [9] demonstrated the specific charge states and energy loss distributions of 300 MeV/u U-73+ ions channeled in a 120 μm thick <110> Si crystal. This experiment was not the case for HWC channeling, since: a) for this RHI energy the HWC channeling may occur at a crystal thickness of order of several μm, and b) it was the case of axial channeling.

As a positively charged particle impinging on atomic planes of a crystal with the so called "critical angle for channeling", it is trapped between atomic planes but moves free along them. The critical channeling angle depends both on the charge and mass (or relativistic energy) of the projectile. In the case of high-Z isotopes the change of the mass number A = Z + N only little bit changes the critical channeling angle, which is proportional to \( \sqrt{Z/N} \). In contrary, in the case of low-Z RHI (e.g. H, Li, Be isotopes) the change of A can be rather large, that means the HWC channeling should be sensitive to A and probably can serve as the mass filter.

In this work we present the results of computer simulations of channeling in HWC of Hydrogen (protons (p), deuterons (d) and tritons (t)) and Lithium (\(^{6}\)Li, \(^{7}\)Li) isotopes with kinetic energy \( E_b = 300 \text{ MeV/u} \) (the same as in earlier experiment [9]) passing through a (220) Si crystal, with the use of the computer code BCM-2.0 [10].

Possible applications of HWC-channeling of RHI are discussed, e.g. as fragments defectors, splitters as well as the charge Ze and mass number A filters.

2. Simulation procedure

The RHI trajectories under HWC channeling were simulated using numerical solution of the equations of motion using the com-
puter code “Basic Channeling with Mathematica®” BCM-2.0 [10]. The equations of motion describing RHI planar channeling are:

\[
\begin{align*}
\gamma M \ddot{x} &= -\frac{\partial U(x)}{\partial x}, \\
\gamma M \dot{z} &= 0.
\end{align*}
\]

Here, \(x(t)\) is the coordinate transverse to the crystal planes, \(z\) is the longitudinal (parallel to the crystal planes) coordinate, \(M\) is the rest mass of RHI, \(\gamma\) is the relativistic factor, and \(U(x) = ZeV(x)\) is the potential energy of RHI with electric charge \(Ze\) in the potential \(V(x)\) formed by periodically arranged crystal planes. The initial conditions for Eq. (1) are: the RH entrance point into a crystal \(x(t = 0)\) and the x-component \(\dot{x}(t = 0) = v_x(t = 0) = v(t = 0)\cdot \sin \theta\) of its initial velocity \(v(t = 0)\), where \(\theta\) is the incident angle of RHI with respect to the channeling planes. The simulations take into account both the angular spread of the incident RHI beam (different \(\theta\)) and the different points of incidence \(x(t = 0)\) into the HWC.

The HWC thickness used is \(L = \lambda/2\), where the half wavelength \(\lambda/2\) depends on the distance \(d_{p}\) between channeling planes and the critical channeling angle \(\theta_{c}\) (see, the recent discussion on \(\theta_{c}\) for the ion channeling in [11]):

\[
\frac{\lambda}{2} = \frac{\pi d_{p}}{2\theta_{c}}, \quad \theta_{c} = \frac{2V_{0}z}{\beta^{2}E}.
\]

In Eq. (2) the critical channeling angle \(\theta_{c}\) for RHI depends on three parameters: \(Z\) – the atomic number of the RHI (or proton number \(Z\)), \(E = \gamma M c^2\) – initial total energy of RHI \((M\) is its mass) and initial velocity \(\beta = \frac{c}{\sqrt{1-\frac{\gamma^2-1}{\gamma^2}}}\) (\(c\) is the speed of light). In addition, it depends on the maximal value of potential energy \(U_{0}\) of the unit charge in the continuous potential for planar channeling (e.g. 38.6 eV for (220) planar channeling in Ge). Thus, for equal \(Z\), \(\gamma\) and \(\beta\) the \(\theta_{c}\) value depends also on the neutrons number \(N\), since \(M = Z \times M_{p} + N \times M_{n} - \varepsilon\) (\(\varepsilon\) - is the binding energy). Obviously, this can be very important for low-Z isotopes.

The name HWC arises in the following way: consider the inter-planar potential \(V(x) = kx^2/2\) where \(k = 8V_{0}/d_{p}^{2}\) and \(V_{0} = V(d_{p}/2)\). The Eq. (1) is now the equation for harmonic oscillator. The period of oscillations inside this channel equals to \(T = \pi d_{p}\sqrt{2M/\varepsilon V_{0}}\). The distance which RHI penetrates along crystal planes during a half of \(T\) is

\[
\frac{\lambda}{2} = \frac{\nu T}{2} = \frac{\beta c}{2} \pi d_{p} \sqrt{\frac{M}{2Z V_{0}}} = \frac{\pi d_{p}}{2\theta_{c}}.
\]

and is called “the half-wavelength” [1,2]. The Table 1 presents the parameters defined by Eq. (2) for low-Z (isotopes) and high-Z-high-A RHI.

One should mention, that the half wavelength \(\lambda/2\) depends on the RHI energy as \(\sqrt{\gamma}\), that means for planned at FAIR RHI energies \((\gamma = 25 \div 30)\) the HWC thickness can be rather large, which is important from technical point of view and even heavy W crystal (greater \(U_{0}\) and greater deflection angle) can be used.

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**Table 1**

| \(|220|\) Ge crystal, \(V_{0} = 38.6\,\text{eV}, d_{p} = 2.0\,\text{Å}, E_{k} = 300\,\text{MeV/u}|\) | \(\rho\) \(A/Z\) | \(1\) | \(2\) | \(3\) | \(4\) | \(5\) | \(6\) |
|---|---|---|---|---|---|---|---|
| \(\theta_{c}\) (mrad) | 0.382 | 0.270 | 0.221 | 0.270 | 0.221 | 0.200 |
| \(\lambda/2\) (μm) | 0.822 | 1.162 | 1.424 | 1.162 | 1.424 | 1.574 |

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**Fig. 1.** Simulated beam intensity diagram for the protons passed through a (220) germanium HWC as a function of the crystal rotation angle \(\theta\) and of the beam deflection angle \(\theta_{def}\). The beam angular spread \(\Delta \theta = 0.03\,\text{mrad}\). The beam angular range \(\Delta \theta = 0.03\,\text{mrad}\).

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**3. Low-Z RHI (isotopes) beam deflection and splitting by HWC**

**3.1. HWC channeling of 300 MeV/u protons, deuterons and tritons in (220) Ge**

The HWC channeling is more sensitive to \(A = Z + N\) in the case of low-Z ions. Here, we demonstrate it for hydrogen isotopes, when only the mass number \(A\) is changing due to change in the neutron number \(N\). The Table 1 presents the key parameters for HWC channeling of \(p\), \(d\), \(t\), while the Fig. 2 shows simulated trajectories (top row) and angular distributions (bottom row) in deflection angles of H- isotopes \(p\), \(d\), \(t\) with energy \(E_{k} = 300\,\text{MeV/u} channeled in (220) Ge HWC. The crystal thicknesses were equal to half wavelength \(\lambda/2\) for protons (a), deuterons (b) and tritons (c) correspondingly. The incident angle was equal to \(\theta_{c}/2\), which is the most appropriate orientation to realize the mirror effect in the HWC channeling [2].

As it follows from Fig. 2, the trajectories of H-isotopes in a HWC become different with penetration depth (z-axis). The splitting of the incident beams into two components (moving “to the left” and “to the right”) is clearly seen and arises due to different directions of H-isotopes velocities after channeling in a HWC (see, the caption to Fig. 2). The distributions are quite different, in accordance with Eq. (2), that means, they are sensitive to the \(A(N)\) value. The magnitudes of deflection angles are of the order of the critical channeling angles. Each angular distribution contains the well-pronounced maximum, corresponding to the deflection angle \(\theta_{def} \approx \theta_{c}\) of the chosen isotope. That means, if one places a RHI detector at this angle, one can select necessary isotope component from the mixed ion beam.
angles for The Fig. 3. through Top Fig. 2. The flected details Let row: indicate ions, simulated p, d, and t trajectories with $E_k = 300$ MeV/u for 20 different points of incidence. Bottom row: distributions in deflection angles $\theta_{\text{def}}$ of p, d and t passed through a (220) Ge HWC, obtained with $N_{i,\text{tot}} = 10^5$ trajectories (the points of incidence are uniformly distributed within $-\frac{\pi}{2} < x(t = 0) < \frac{\pi}{2}$). The red, blue and green lines indicate the p, d and t, correspondingly. The angle of incidence is half of critical channeling angle, $\theta = \theta_i/2$, and angular spread of incident beam $\Delta \theta = 3 \mu rad = 0.3/100$.

Here, the index $i$ denotes p, d, t and an interval $\theta_{\text{def}1} < \theta < \theta_{\text{def}2}$ is the full width at half maximum of simulated angular distribution for an isotope, corresponding to his HWC thickness, (Fig. 2). For HWC channeling of protons $\theta_{\text{def}1} = 0.35 \mu rad$ $\theta_{\text{def}2} = 0.40 \mu rad$, and we obtain $\varepsilon_i = 0.604$ for protons, 0.179 for deuterons and 0.042 for tritons, respectively. The results of calculations of separation efficiencies for channeling in HWC of three different thicknesses, corresponding to p, d and t HWC, are presented in the Fig. 3. Thus, one may conclude, that HWC channeling of low-Z RHIs probably could be suitable to separate the low-Z isotopes by selecting the appropriate HWC and incident angle.

3.2. HWC channeling of 300 MeV/u $^6$Li, $^9$Li and $^{11}$Li in (220) Ge

Let consider heavier low-Z isotopes, $^6$Li ($Z = 3$, $A = 6$) and $^9$Li ($Z = 3$, $A = 9$). Since the ratio $A/Z$ for $^6$Li and for $^9$Li are equal to that for $A/Z$ of deuteron and triton, the distributions in deflection angles due to HWC channeling are the same, so we can use the same HWC for separation of these isotopes. In fact, this is some kind of scaling with respect to $A/Z$ ratio.

For separation of isotopes with close values of the ratio $A/Z$, for example $^9$Li and $^{11}$Li, the HWC can be also applied, but the efficiency of the separation is not so pronounced as in the case of hydrogen isotopes, Fig. 3. As it follows from simulations (see,
in the Fig. 4 and 5), one can improve the separation efficiency, if decreasing of the angular spread of incident beam.

3.3. HWC channeling of 300 MeV/u $^6$Li and $^{11}$Li in (220) Ge: decreasing twice the angle of incidence

Now let the angle of incidence be a quarter of the critical channeling angle, $\theta = \theta_c/4 = 0.07$ mrad, the crystal thickness is the same as in Fig. 2, and the angular spread of incident beams $\Delta \theta = \theta_c/10$. The simulated distributions in deflection angle $\theta_{\text{def}}$ are shown in Fig. 6.

The separation in deflection angles of $^6$Li and $^{11}$Li now is clearly seen within deflection angles 0.06 mrad $< \theta_{\text{def}} < 0.18$ mrad, that means the primary mixed ($^6$Li + $^{11}$Li) beam is separated into the deflection angles again. The shift of distributions maxima to lower deflection angles compared to Fig. 2 and Fig. 4 is due to the change of trajectories, since for the same point of incidence the oscillation period in a (220) channel decreases following the decrease in the angle of incidence (equivalent, decrease in transverse velocity).

4. Conclusions

The computer simulations of the angular distributions of relativistic heavy ions (RHI) channeled in a HWC demonstrated that besides the beam energy, crystal thickness and alignment, the HWC channeling is sensitive to a charge $Ze$ and a mass number $A$ of the ions.

- For low-Z RHI (isotopes) the simulations demonstrate the sensitivity of angular distributions after a HWC to the mass number $A$, thus to the neutron number $N$. This isotopic effect for
channeling was never observed before. One can suppose, the HWC channeling probably can be used not only as the beam deflector, but also as isotope mass $A$ filter.

- For high-Z RHI the beam deflection angles through the HWC mirroring effect are of the order of the critical channeling angle $\theta_c$, and the isotopic effect is negligible. Possible applications of the HWC channeling of RHI beams are non-expensive secondary beam deflectors or splitters, similar to the applications of bent crystals in high-energy particle physics [12].

We hope, the simulations of RHI channeling in a HWC will contribute to this field and will be useful in preparations of new atomic physics experiments for Super-FRS Experiment Collaboration at FAIR [7,8].

To conclude, the search for the new types of detectors and methods of beams steering, splitting and deflection in high-energy particle and nuclear physics is still in progress. These are already mentioned experiments [1–5] as well as recent experiments on use of Cherenkov radiation as the velocity filter of relativistic fragments [13] and the suggestion to use the Cherenkov radiation as a mass filter [14] of relativistic isotopes.

Finally, the deflection of a 1.3 GeV proton beam by a system formed by fan-oriented 10 thin silicon wafers was studied recently both theoretically and experimentally [15,16]. Every wafer was in fact the HWC. The authors suggested that this novel crystal technique could be useful for creating high-quality ultra-stable low-emittance proton beam for medical and biological purposes. The simulations of efficiency of this system to rotate to a given angle the sub-GeV heavy ions (e.g. C-12 for heavy ion therapy) are in process and the results will be published separately.

Another interesting suggestion is connected with extension of the concept of HWC- channeling to the concept of $(n+1/2)$ wavelength channeling $(n$ is integer number) [15,16]. For the goal of particles deflection, this extension allows a use of much thicker crystal and thus to avoid the technical problems with microns-thick crystals. Based on this concept the system formed by fan-oriented 10 thin silicon crystals (200 $\mu$m thick each) was recently suggested and tested to deflect the GeV proton beams [15,16].

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References